

Dynamic Modeling of the SMAP Rotating Flexible Antenna

Reza D. Nayeri

NASA Jet Propulsion Laboratory

June 20, 2012



© 2012 California Institute of Technology
Government Sponsorship Acknowledged





Overview: SMAP Project

- **The Soil-Moisture Active/Passive (SMAP) mission will provide global measurements of the soil moisture and its freeze/thaw state**
- **The accuracy, resolution, and global coverage of SMAP soil moisture and freeze/thaw measurements help us :**
 - ❖ Quantify key parameters in the global hydrologic and carbon cycles
 - ❖ Extend weather/climate forecast capabilities
 - ❖ Enhance understanding of processes that link the water, energy and carbon cycles
- **Launch is planned for 2014**



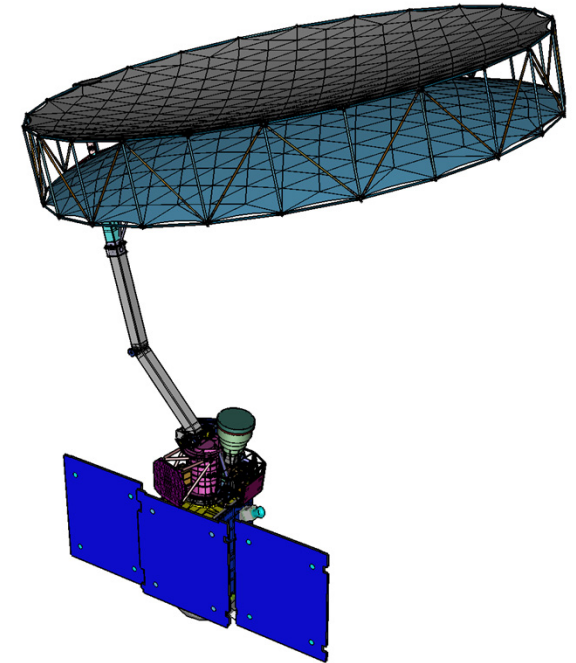
<http://smap.jpl.nasa.gov/mission/>



Overview: SMAP Dynamic Modeling

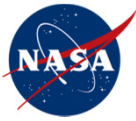
Key Characteristics

- **Balancing:** the goal is to null out any mass imbalance by using passive ballast masses prior to launch
 - There will be no active on-orbit balancing mechanism
 - Mass imbalance comes from two sources: (a) Spun CM offset, and (b) Spun Products of Inertia (POI)
- **Momentum Compensation:** the Control system maintains a zero net angular momentum system, by nulling the spun momentum using Reaction Wheels
- **Frequency Separation:** Structural modes are way above the control bandwidth to minimize the Control Structure Interactions (CSI)



Dynamic Model Applications

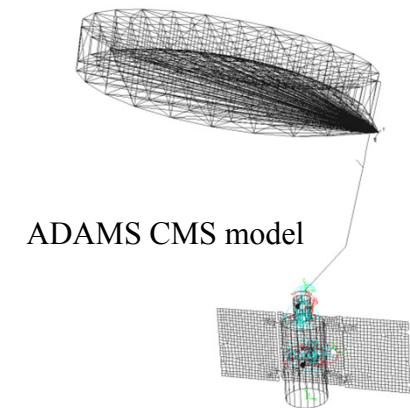
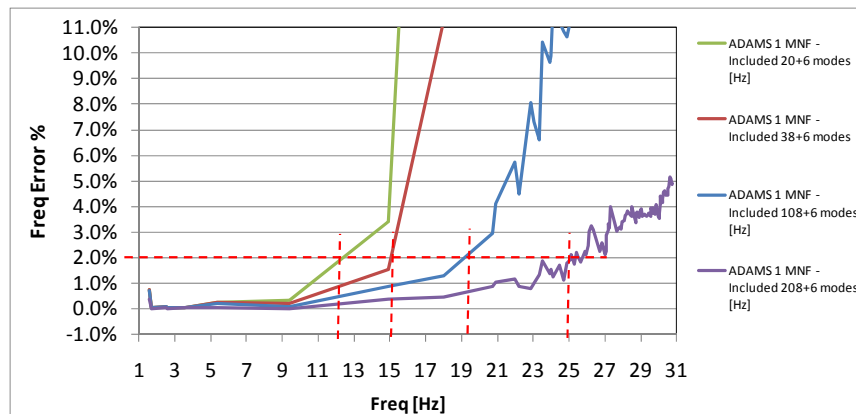
- **Pointing Error Performance:** Dynamic models are used to quantify the beam boresight pointing errors due to dynamic sources, and compare against the project pointing requirements
- **Control Design Verification:** Used as nonlinear plant models for the time domain control analysis and verification of the stability margins against the project requirements



ADAMS CMS Model Development

Modal Truncation Study:

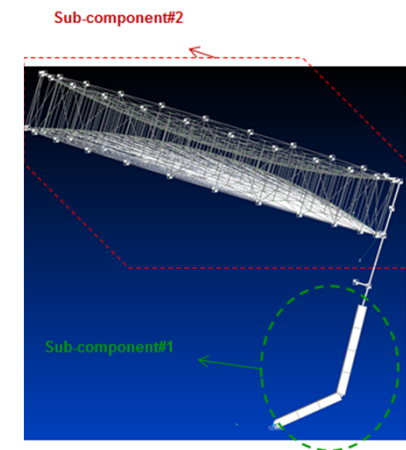
- Increased the number of component modes in the CMS model until ADAMS System Eigenfrequencies match NASTRAN within a desired accuracy in the freq range of interest



ADAMS CMS model

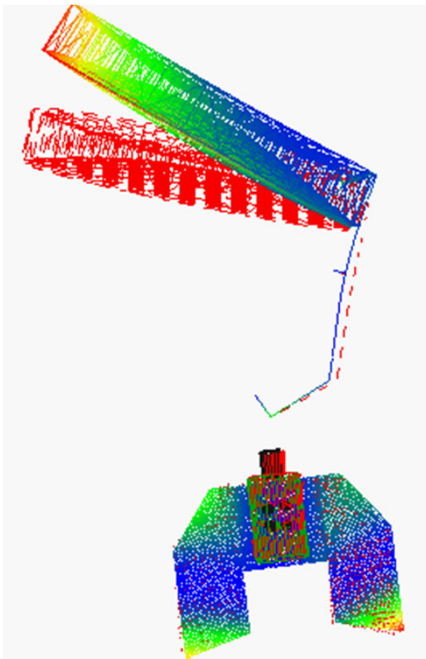
Splitting Large Components into Multiple Sub-Components:

- The CMS formulation uses linear modal superposition, and for that it assumes small flexible body deformations
- Splitting large components into multiple bodies increases the CMS accuracy, since the nonlinear behavior of large deformations, is captured using a piecewise linear system

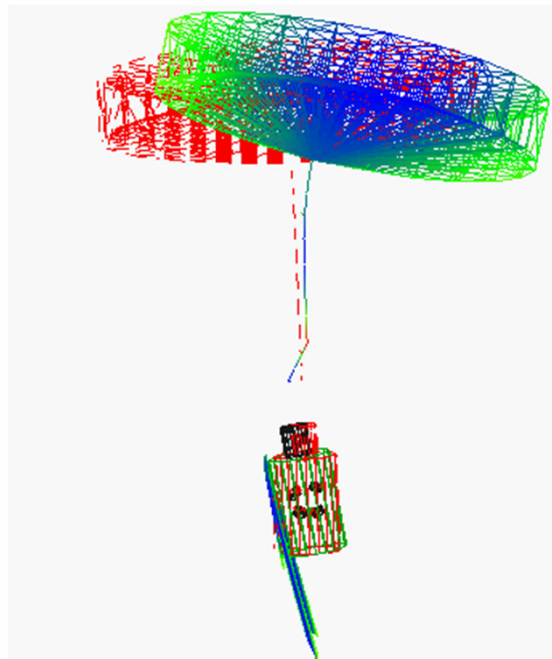




ADAMS Observatory Mode Shapes



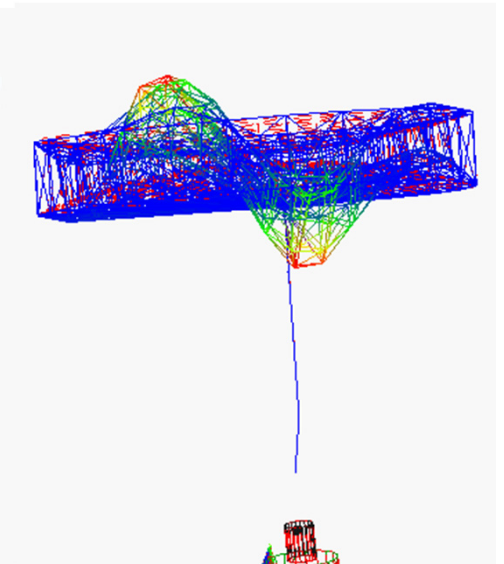
1st antenna nodding about Y-axis



1st antenna tip-tilt about X-axis



1st Solar Array Bending mode

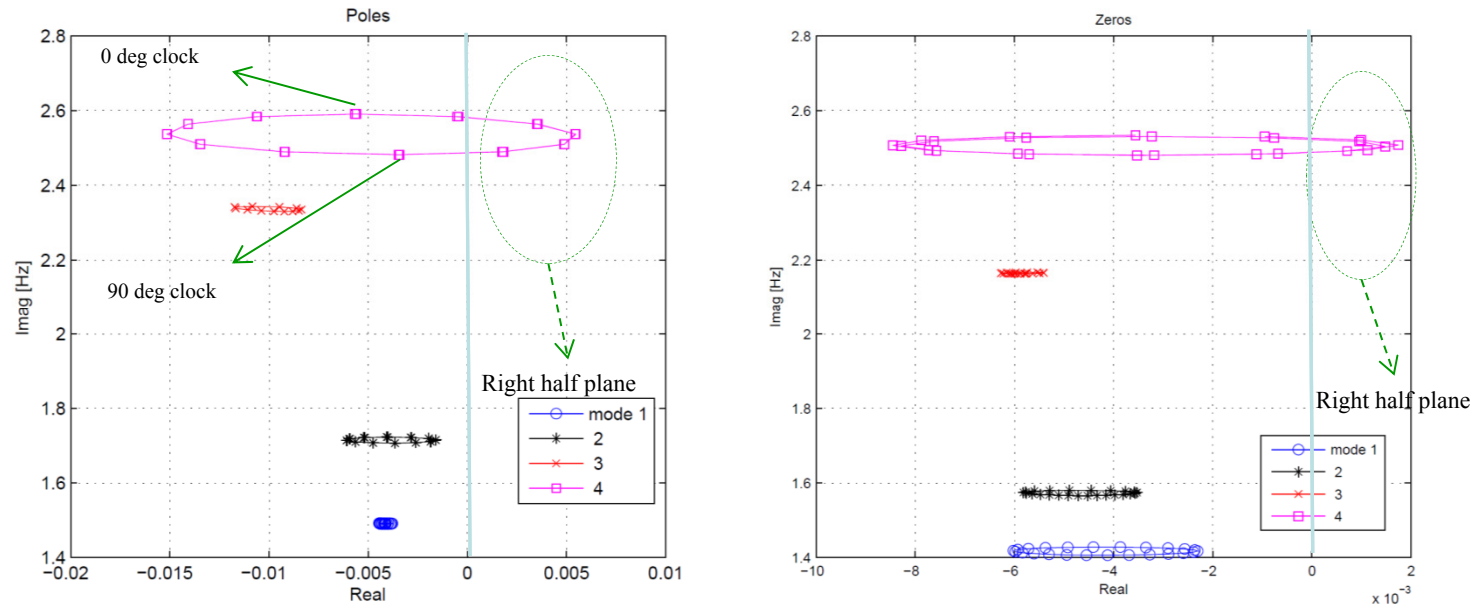


1st Reflector Mesh Mode



Time Varying Nature of the Problem (1 of 2)

Poles & Zeros change as a function of instrument clock angle while spinning



- System poles and zeros in the complex plane (Root-Locus) move on ellipse-type shapes as a function of clock angle
- For each mode, the pole/zero ellipse repeat on itself every 180 deg (clock angle)
- For some clock angles the system poles/zeros may go to the right-half complex plane



Time Varying Nature of the Problem (2 of 2)

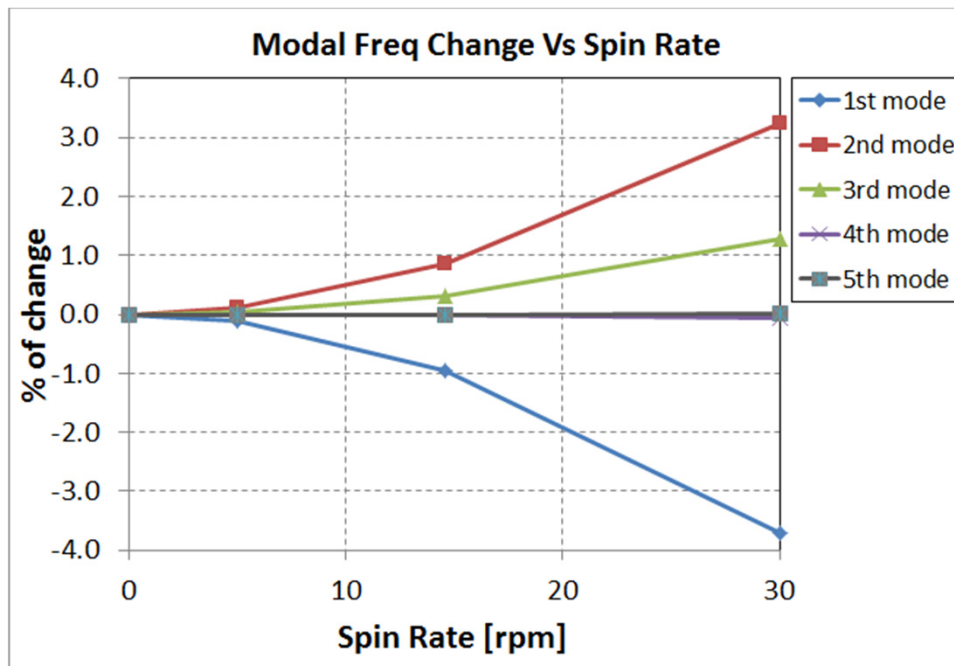
- The system at the spinning state is a Time Varying problem, and the Linear Time Invariant (LTI) stability assumptions do not hold.
 - System has significant time-varying periodic features → system stability can NOT be assessed using a “standard” LTI transfer function approach
 - The poles/zeros of the linearized model may instantaneously go to the right half plane, but that alone is not an indication of instability of the system
- For a ***time varying periodic*** system like this, ***Floquet*** analysis is the right approach to assess stability
- Final confirmation of system robustness and stability performance should be done using nonlinear time domain simulations



Spin Rate Effects on the System Eigen-freq

Dependency on the Spin rate:

- Centrifugal and gyroscopic effects, cause system natural frequencies to change as a function of spin rate (spin stiffening/softening effects)
 - The dependency is minimal if the spin freq is way below the natural frequencies



Computing the freq and damping from a complex modal analysis:

$$\Omega_i = \alpha_i + j\beta_i \text{ [Hz]}$$

$$f_i = \sqrt{(\alpha_i^2 + \beta_i^2)} \text{ [Hz]}$$

$$\zeta_i = \cos(\tan^{-1}(\beta_i / \alpha_i))$$



Damping Implementation in the CMS Model (1 of 2)

Goal:

- Projects normally desire to enforce a damping policy at the observatory (system) level. To that end, in a CMS model one need to define the damping values at the component level in order to enforce a desired system level damping

Challenges:

- User can specify the modal damping for the component modes. However, once the components get synthesized with the rest of the observatory model, the observatory (system) modal damping is going to be different
- Moreover, component modes can couple, making it impossible to obtain exactly the desired modal damping for all system modes

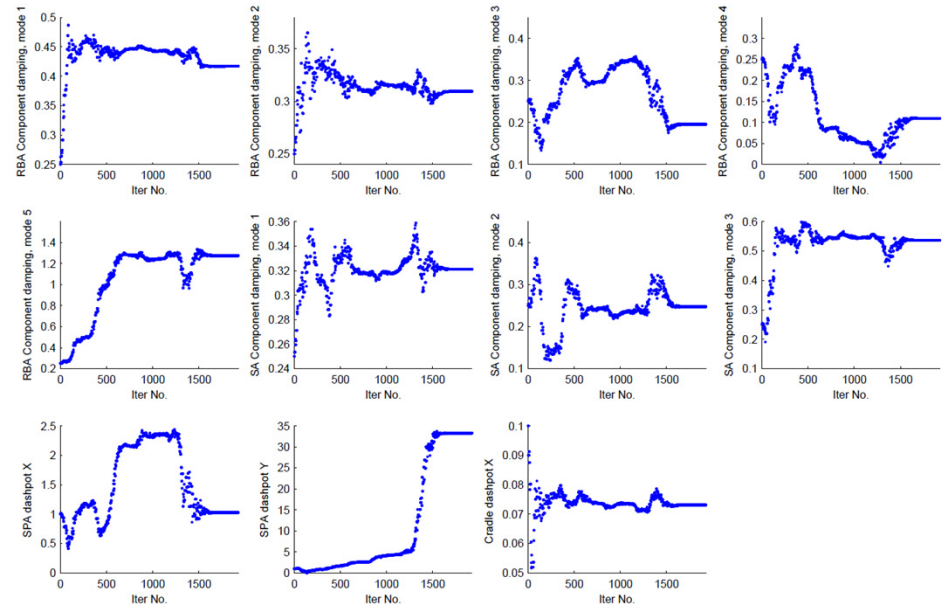
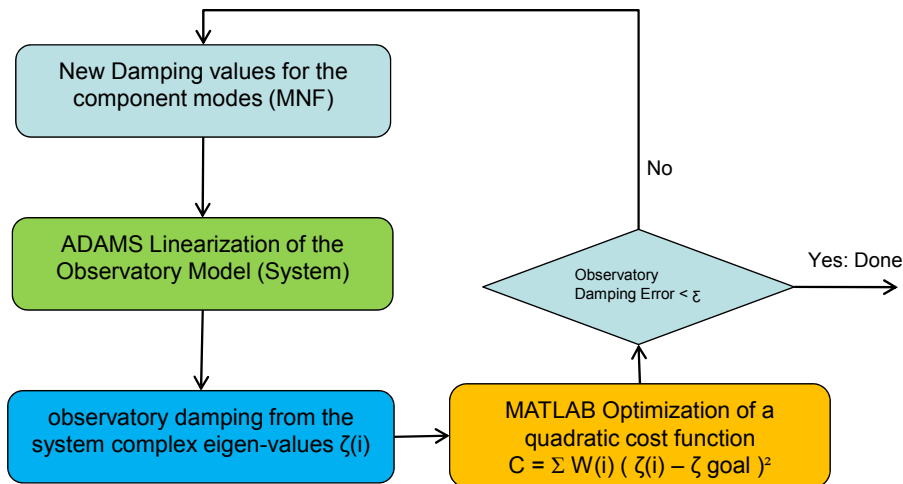
Approach:

- An optimization program was developed in MATLAB in order to tune the observatory (system) modal damping by iteratively changing the component modal damping values



Damping Implementation in the CMS Model (2 of 2)

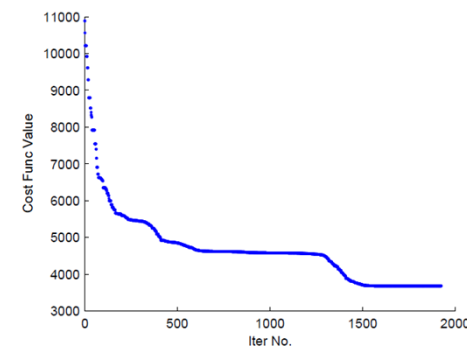
The optimization algorithm is implemented in MATLAB, having ADAMS in the loop



➤ The first step in this process is the **Component Mode Sorting**, which is the process of identifying the component modes that dominantly affect the primary modes of the system. We only need to optimize those dominant component modes and not all of them.

➤ It is recommended to over-damp (> 10 %) the high freq residual component modes, which effectively means ignore the inertia effects but keep the compliance

➤ Random search optimization techniques are more suitable to handle this problem with a discontinuous error surface





Evaluation of CMS Model for Spinning Dynamics

Objective: The goal of this study was to determine whether the ADAMS Component Mode Synthesis formulation captures the spin-induced dynamic behavior of rotating structures

Equation of motion for a flexible spinning system in its rotating frame:

$$\underbrace{\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{B}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t)}_{\text{inertial, elastic, and damping terms}} + \underbrace{\mathbf{B}(\boldsymbol{\Omega} \times \mathbf{u}(t)) + \mathbf{M}(\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{u}(t))) + \mathbf{M}(2\boldsymbol{\Omega} \times \dot{\mathbf{u}}(t))}_{\text{spin induced terms (gyroscopic and centrifugal effects)}} = 0$$

inertial, elastic, and damping terms

spin induced terms (gyroscopic and centrifugal effects)

Approach:

A benchmark spinning structure with 5 Beam elements resembling the SMAP instrument was created in NASTRAN. Based on that, two equivalent models (twins) developed in ADAMS:

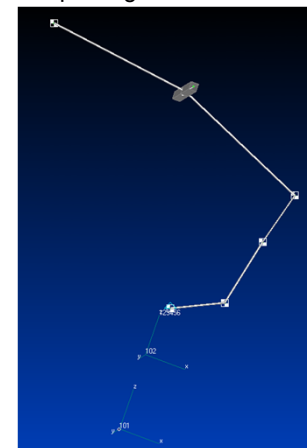
(I) ADAMS Benchmark *Beam* Model (the truth)

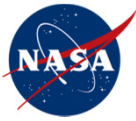
The ADAMS *Beam* model is built directly from the beam physical properties (nonlinear Euler-Bernoulli theory). It truly captures the Gyroscopic and Centrifugal effects (no modal discretization involved)

(II) ADAMS Benchmark *CMS* Model

An equivalent CMS model built in ADAMS by importing the component modes from the NASTRAN model

NASTRAN Benchmark
Spinning Structure



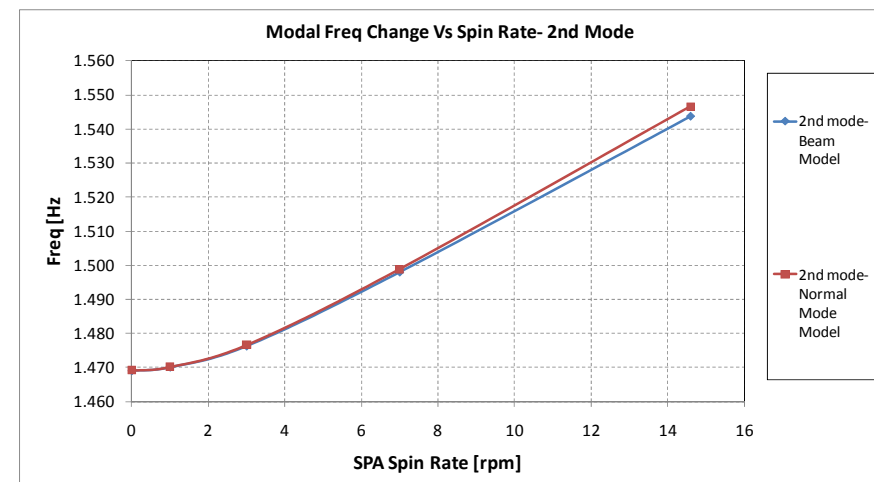
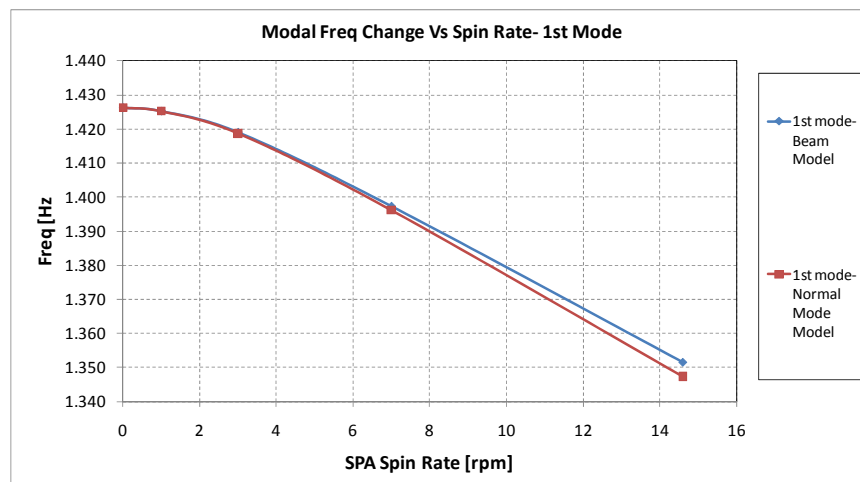


Overview of the Findings

The results comparison showed a very good agreement between the benchmark CMS and beam models.

➤ **Complex eigenfrequencies change due to the spin rate:**

The spin-rate dependence of the natural frequencies for the both models were in close agreement.



➤ **The nonlinear time history results comparison :**

The time history comparisons from the nonlinear simulations at steady state and transient impulse response while spinning, showed a very good agreement between the benchmark CMS and beam models

➤ **Linearized pole/zero & FRF comparisons @ spinning states:** observed close agreements

Conclusion: CMS formulation in ADAMS is sufficiently accurate for capturing spin-induced elastic deformations of the rotating structures



Summary and Conclusions

- Dynamic model development in ADAMS for the SMAP project explained
 - The main objective of the dynamic models are for pointing error assessment, and the control/stability margin requirement verifications
- It was shown that the system at the spinning state is a Time Varying problem, and the Linear Time Invariant (LTI) stability assumptions do not hold.
 - For a time varying periodic system like this, Floquet analysis is the right approach to assess stability
- Damping Implementation in the CMS Model to enforce a system level requirement could be a challenging task
 - Proposed an optimization technique to tune the component mode damping in order to achieve a desired system modal damping
- ADAMS CMS evaluation against an equivalent physical beam model, showed that the CMS formulation in ADAMS is sufficiently accurate for capturing spin-induced elastic deformations of the rotating structures

SCM

Thank you



© 2012 California Institute of Technology
Government Sponsorship Acknowledged

